The Quaternary stratigraphy and geological history of the Australind-Leschenault Inlet area

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Abstract

The Australind-Leschenault area contains 5 Quaternary formations, 3 of which are Pleistocene, and 2 Holocene. The oldest two are: the Australind Formation (a Pleistocene unit of nodular muds and calcareous sands) overlain by the Tamala Limestone. The Eaton Sand, a yellow/orange quartz sand, also is Pleistocene and overlies the Tamala Limestone mostly as a patchy veneer. The Eaton Sand was locally reworked at a later stage in the late Pleistocene into a shoreline ridge that forms the eastern shore of Leschanult Inlet.

The Leschenault Formation and the Safety Bay Sand, are Holocene; the Leschenault Formation is an estuarine unit of sand and mud and the Safety Bay Sand is composed of aeolian and beach sands. The Leschenault Formation was deposited behind a barrier of Safety Bay Sand, and by eastward migration of dunes, the Safety Bay Sand prograded over the Leschenault Formation. Detailed stratigraphic studies show that accumulation of these Holocene units took place in 3 stages: 1) when sealevel stood 2-3 m below present level, 2) when sealevel stood 3-4 m above present level, and 3) at present sealevel. These depositional/historical stages are preserved in the stratigraphy of the Safety Bay Sand as 3 distinct lithologic and/or diagenetically altered units: the Burragenup (oldest), Rosamel and Vittoria Members. In addition modern cementation in marine and subaerial environments is generating 2 other distinct units, the Koombana Beach Rock and Binningup Calcrete.

Introduction

This paper reports the results of research on the stratigraphy of the coastal area of Australind-Leschenault Inlet-Koombana Bay (near Bunbury W.A.) The data, obtained mainly from Quaternary units, provide new information about the Quaternary history of this part of the Swan Coastal Plain and particularly about the development of the barrier dune system during the Holocene.

The study area is situated toward the southern part of the Swan Coastal Plain (Fig. 1) and forms a contemporary coastal deposition area of the Perth Basin (Playford *et al.* 1976). Several major geomorphic units have been described in this area McArthur and Bettenay 1960; Semeniuk and Meagher, 1981b; Table 1). The most eastward in this study area are Bassendean, Spearwood and Blythewood units. Leschenault Inlet forms a narrow lagoon parallel to the coast; within this lagoon are marginal flats, shoals and platforms of sand, and an interior basin of mud. Leschenault Peninsula (Quindalup Dunes), a narrow dune barrier with beach/beach ridge sediments on its ocean side, separates the lagoon from the Indian Ocean. The most westerly occurring geomorphic unit is the submarine shelf. This is underlain mainly by Tamala Limestone, ridges of Holocene beachrock and vast sheets (veneer) of unconsolidated sand/gravel; locally there is basalt and outcrops of estuarine mud.

Stratigraphic sections were examined on natural cliff exposures, in excavations (55 in total), in large costeans (8 in total) and in cores (70 in total). Cores were obtained by percussion drill in unconsolidated sediment sections and by diamond drill (9 cores) through the indurated stratigraphic intervals. Core sites are mentioned throughout the text by a number, e.g. core site 1. Locations of excavations, costeans and cores are shown in Fig. 2. Offshore stratigraphy was studied by diving and samples of indurated stratigraphic units were collected by blasting.

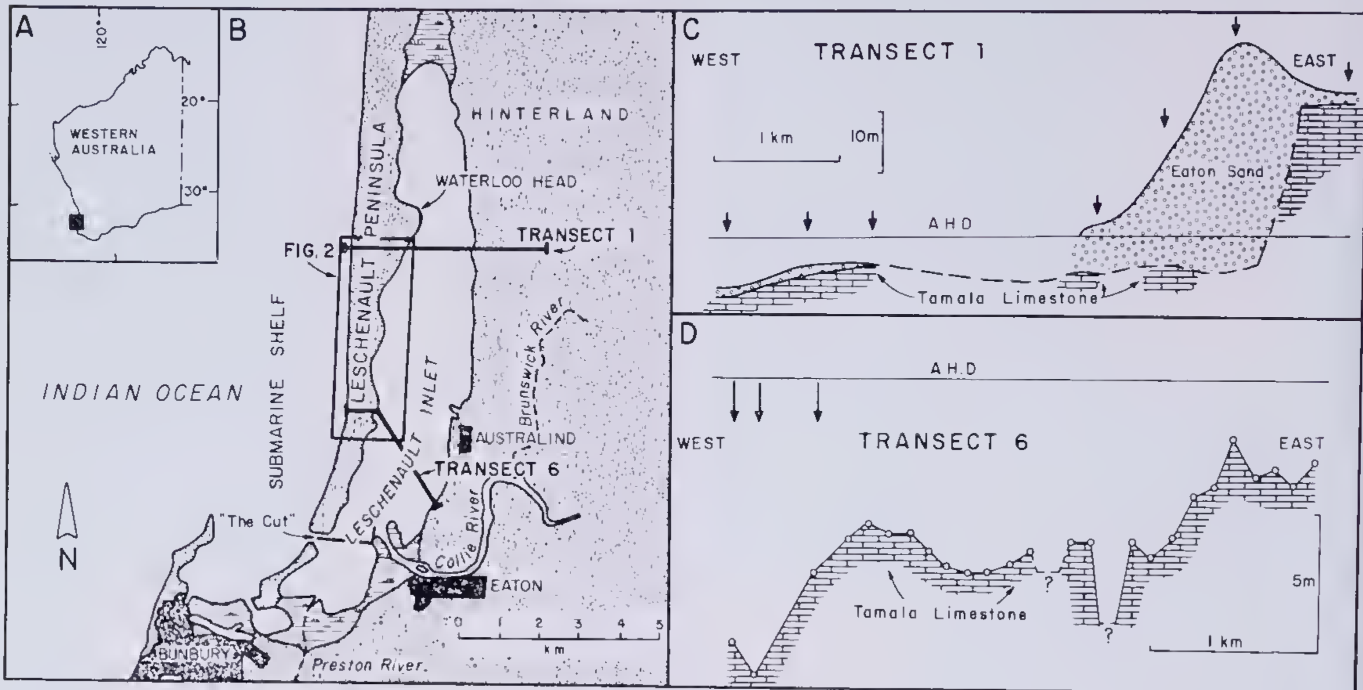

Figure 1.—A and B. Maps showing study area, location of transects and location of more detailed maps. Fig. 2. shows location of additional transects.
C. Cross section showing distribution and stratigraphic relationships of Tamala Limestone and Eaton Sand. Arrows indicate core or auger locations.
D. Cross section showing irregular surface of Tamala Limestone beneath Leschenault Inlet and Leschenault Peninsula as determining by jet-probing and coring. Dot indicates sample position; arrows indicate position of cores.

Table 1

Summary table of terminology of geomorphic units/stratigraphic units within study area

Geomorphic Units (McArthur and Bettenay 1960, Seddon 1972)	Formations (Seddon 1972, Playford *et al.* 1976)	Soil Units (McArthur and Bettenay 1960, Bettenay *et al.* 1960, Seddon 1972)	This paper
Bassendean Dune System	Bassendean Sand	Bassendean Soil Association	Adjoins east margin of study area
Spearwood Dune System	Tamala Limestone	Cottesloe Soil Association Karrakatta Soil Association	Tamala Limestone; stratigraphic equivalents of Cottesloe Soil and Karrakatta Soil are termed Eaton Sand
Quindalup Dune System	Part of Safety Bay Sand	Quindalup Soil Association	Burragenup, Rosamel, Vittoria and Binningup members of Safety Bay Sand
Beach and nearshore sediments	Part of Safety Bay Sand	Not applicable	Vittoria and Koombana members, of Safety Bay Sand
Inlets, lagoon and lakes	Not named	Vasse soil Association	Leschenault Formation

Stratigraphy

Five Quaternary formations, (3 of them new) have been encountered by mapping and coring in this area. In sequence down the profile these are:

5. Safey Bay Sand
4. Leschenault Formation
3. Eaton Sand
2. Tamala Limestone
1. Australind Formation

} —Quaternary } —Kwinana Group

They rest on sediments assigned to the Warnbro Group of Early Cretaceous age (J. Backhouse 1982 pers. comm.).

The main grain types and other compositionally distinct components of sediments, that were used to distinguish either sedimentary suites or end-member sediment types, are as follows: 1) quartz grains, 2) skeletal (Ca CO_3) grains (oceanic assemblages are distinguished from estuarine assemblages), 3) rutile and other heavy mineral grains, 4) calcareous mud, 5) clay-mineral mud, 6) organic matter and humus, 7) sediment-staining agents (grey due

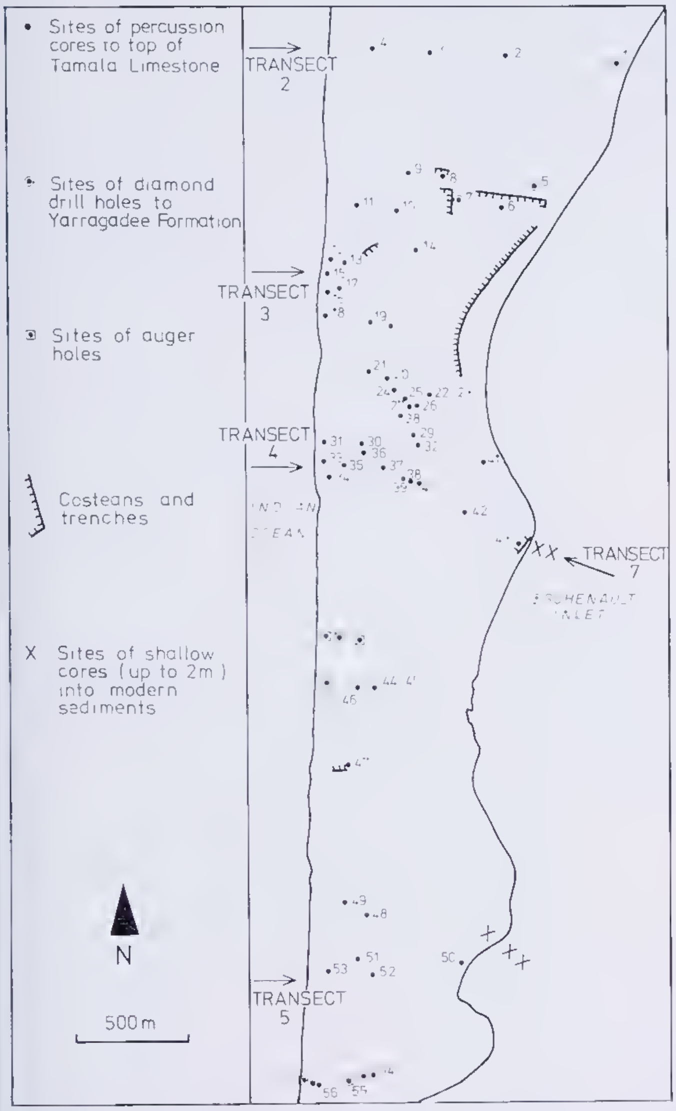

Figure 2.—Map showing location of various stratigraphic sampling sites and core sites, as well as location of transects shown in Figs. 3, 4, 5 and 7.

to humus or pyrite; orange and brown due to geothite), 8) sediment-cementing agents (cryptocrystalline $CaCO_3$ = calcrete; fine to medium crystalline $CaCO_3$ = sparry calcite; geothite, pyrite).

Australind Formation

Definition and characteristics: The Australind Formation is the name proposed for the sequence of colour variegated nodular-cemented calcareous mud, sand and shelly mud that occurs between Warnbro Group and Tamala Limestone.

Derivation of name: After Australind, grid reference 371888, Collie 1:250 000 sheet.

Type section: Core site 36 is designated as the type section.

Distribution: The unit has been intersected in core sites 1, 5, 35, 36, 46 (Fig. 2). It also is known to occur under the east shore of Leschenault Inlet.

Geometry and thickness: The formation is 3 m thick in southern parts of the Leschenault Peninsula but is missing or thin (< 50 cm) in the areas around core sites 7 and 5. Its thickness is variable (Fig. 3), probably as a result of erosion.

Lithology: There are 4 sediment types in the formation and these occur interlayered or mottled with each other. Colour mottles of brown, orange and cream are common. The sediments are:

(1) brown/orange or grey calcareous mud
(2) brown or grey shelly calcareous mud
(3) brown to cream calcareous sands
(4) lithoclast (carbonate rock fragment) gravel.

The calcareous sand commonly is cemented by $CaCO_3$ so that there are cemented sand layers and nodules dispersed through mud layers. The calcareous mud also is cemented in patches into nodules. Cementation in all lithologies results in cream-coloured nodules.

The arrangement of sediments in the formation is described best by the type sequence (Site 36):

AHD
−11.12m

Top: brown calcareous clay with limestone pebbles (= soil)	10cm
Lithified calcareous sand	45cm
Interlayered muddy calcareous packstone/wackestone light grey and dark grey in colour with horizons of cemented granule-sized nodules	75cm
lost interval	48cm
brown calcareous packstone with cream granule-sized cemented nodules	27cm
variegated brown/orange calcareous clay	75cm
variegated brown/orange calcareous clay with granule-sized shelly nodules	15cm
Bottom: ferruginous rock of the Warnbro Group.	

Stratigraphic relationships: The unit rests disconformably on either ferruginous rock or weathered sediments of the Warnbro Group. The top of the unit, marked by rubble, soil and lithoclasts, is disconformably overlain by Tamala Limestone.

Age: G. W. Kendrick (1979, pers. comm.) has identified the following molluscs: *Alba monile* (A. Adams), *Cantharidus (Phasainotrochus)* sp., *Diala lauta* (A. Adams), *Hydrococcus graniformis* Thiele, *Mitrella (Dentimitrella) lincolnensis* (Reeve), *Nassarius* fragment. [probably *N. pyrrhus* (Menke)] and *Tellina (Pinguitellina)* sp.

The fauna is Quaternary and is suggestive of the mid Pleistocene (Kendrick, pers. comm.). On basis of fauna and unconformable relationship to the underlying formation, the Australind Formation is tentatively assigned a Pleistocene age.

Discussion: The lithology and molluscan fossils suggest that the Australind Formation accumulated in coastal lagoons not unlike Leschenault Inlet today. However there is overprint of $CaCO_3$ cementation and colour mottling on the sediments; the latter probably is due to pedogenesis associated with the unconformity at the top of the unit.

Tamala Limestone

The Tamala Limestone (Playford *et al.* 1976; = "Coastal Limestone") crops out in the Leschenault area on the submarine shelf, on the hinterland near Australind and locally along the beach face of the peninsula. On the peninsula the limestone top was the target horizon for the shallow coring programme. Additionally, the top of the formation was investigated for the Public Works Department in 1962 by probing across Lescenault Inlet (Fig. 1D).

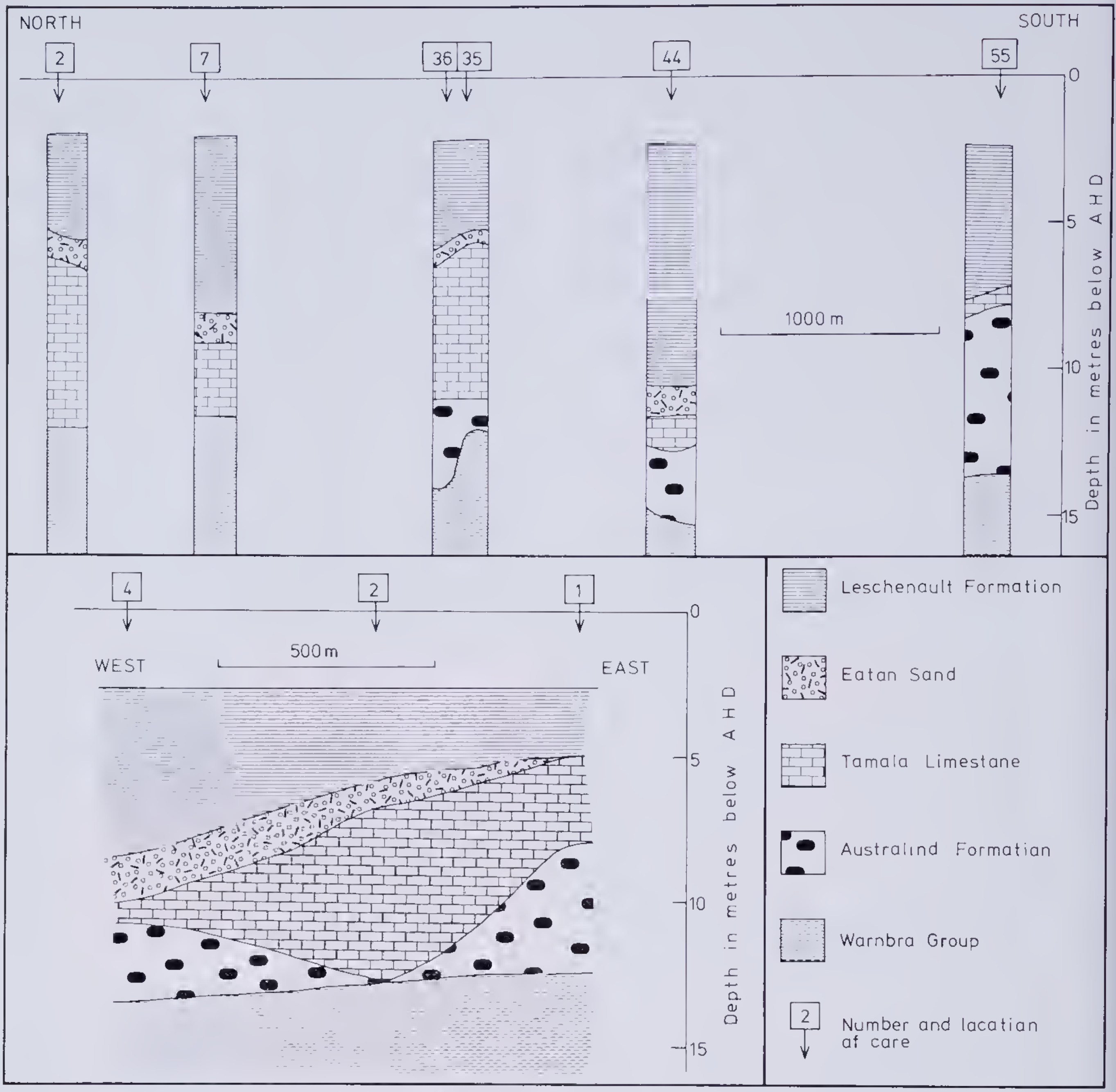

Figure 3.—Distributian and relationship of 5 stratigraphic units under Leschenault Peninsula.

Distribution: The Tamala Limestone was intersected in nearly every core; it has been traced under Leschenault Inlet in two transects; it forms much of the submarine shelf offshore and occurs in the subsurface on the hinterland (Fig. 1C). Apart from small local areas where it has been eroded or not deposited (e.g. around residual knolls of Bunbury Basalt) it may be inferred to be a relatively continuous unit underlying the entire study area.

Geometry and thickness: The depths and overall geometry of the top of the formation is shown for a transect that runs from the hinterland, under both Leschenault Inlet and Leschenault Peninsula, through to the submarine shelf (Fig. 1D). The top is undulating to irregular and has a broad westerly regional slope with a hollow developed under Leschenault Inlet. Diamond drill cores indicate that the formation is approximately 3-6 m thick under the peninsula; cores at site 55 and 56 indicate that the formation thins to south (Figs. 3 and 4). Only surface outcrops were examined in hinterland and offshore localities and thus total thicknesses here are unknown.

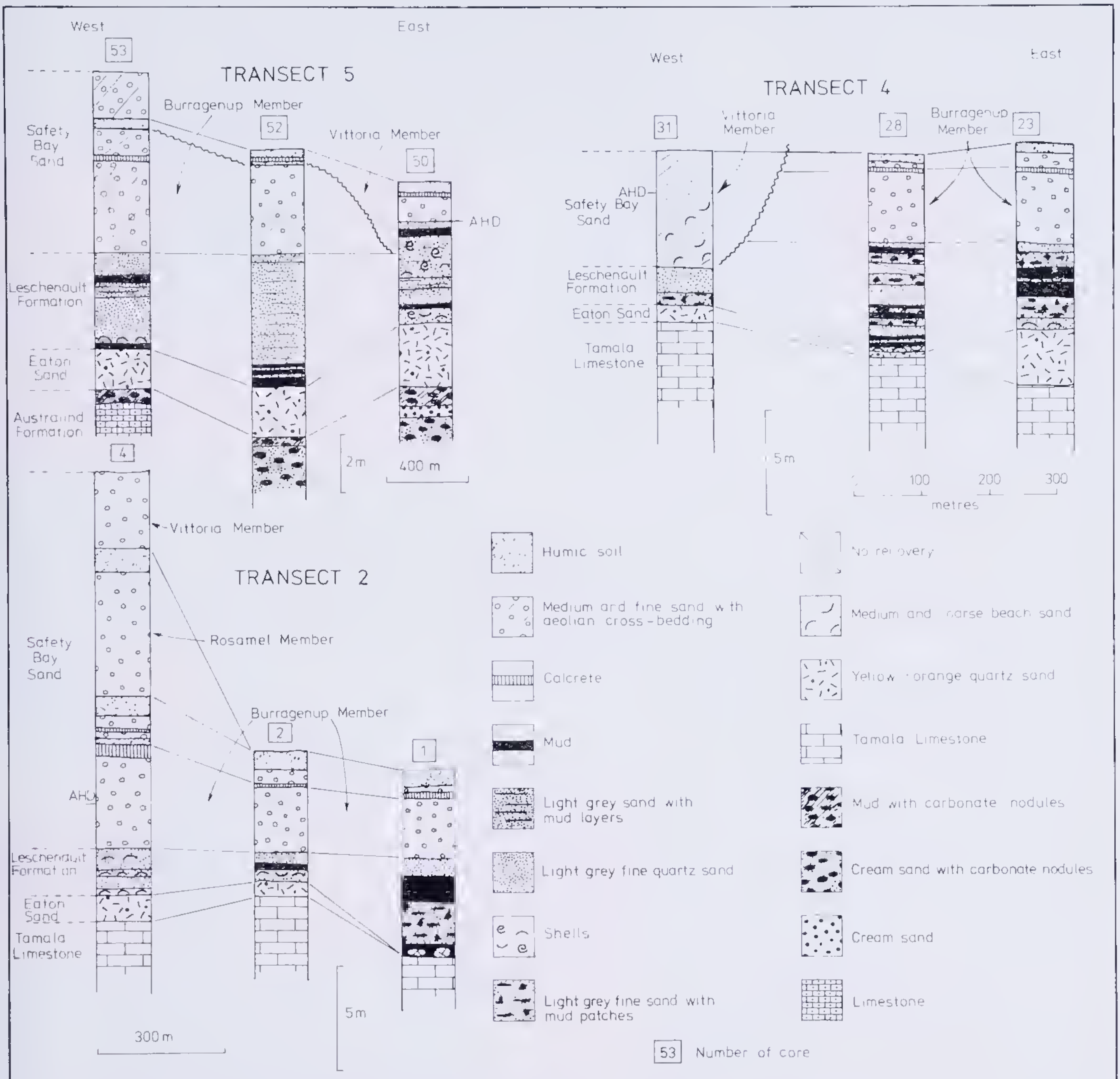

Figure 4.—Stratigraphic columns illustrating lithologic sequences within, and stratigraphic relationships between Australind, Tamala, Eaton, Leschenault and Safety Bay formations.

Lithology: Lithologically, the Tamala Limestone is varied. There are 4 main sediment or limestone types in the formation; these are:

1. quartz skeletal grainstone, composed of medium sand grains
2. shelly, lithoclastic, quartz skeletal grainstone composed of medium to coarse sand grains and gravel-sized lithoclasts and shell
3. skeletal packstone composed of sand grains with interstitial calcareous mud
4. lithoclastic skeletal packstone similar to (3) above but with lithoclast gravel.

Fauna that comprises the skeletal grains in the limestone include a variety of foraminifers, molluscs, calcareous algae debris and fragmented echinoids.

The formation mostly is comprised of quartz skeletal grainstone. However, there are thick layers of shelly, lithoclastic quartz skeletal grainstone. The other sediments (packstones) are confined largely to filling cavities or vugs in indurated grainstones. Locally, however, skeletal packstone occurs as a metre-thick sheet interlayered with quartz skeletal grainstone. The sediments are in various stages of induration, ranging from fully indurated by sparry calcite and calcrete (40%), to weakly indurated (40%), to totally uncemented (20%). Sheets of mottled, massive and laminar calcrete are relatively more indurated and are developed on top of and within the formation. Other subaerial and pedogenic features (such as colluvial breccia and soil), calcreted root-structures and karst surfaces also are commonly developed at unconformity surfaces both on top of and within the unit. Cemented colluvial breccia is plastered on the surface of the Tamala Limestone on hinterland outcrops. The limestone intersected in core commonly exhibits micro—(millimetre-sized) and macro—(centimetre-sized) vugs, with some openings up to metre-sized. These cavities are mostly filled with deposits of unconsolidated packstone (lithologies 3 and 4 above) indicating infiltration of marine sediment into a subaerially altered limestone.

Stratigraphic relationships: The formation rests unconformably on the Australind Formation, approximately 11-12 m below AHD; the contact is marked by soils. Under Leschenault Peninsula the formation is unconformably overlain by Eaton Sand; the contact is irregular with local relief in the order of 3-4 m. The Eaton Sand locally is absent on protruding knolls or pinnacles of limestone and the Leschenault Formation sediments rest directly on the limestone. In all cases, sediments overlying the Tamala contain reworked pebbles of limestone at the contact. On the hinterland the Eaton Sand unconformably overlies and buries a large cliff cut into the Tamala Limestone (Fig. 1C).

The lithology of the top of the limestone is dependent on the degree that erosion has removed the calcrete capping; the lithology may be 1) laminar calcrete, or 2) massive calcrete, or 3) calcrete cemented calcareous sand, or 4) sparry calcite-cemented calcareous sand. The lithology and geometry of the top of the formation indicates that it is a karstified calcreted surface, and it represents a major Quaternary unconformity.

Age: The age of the Tamala Limestone is considered as Pleistocene in the Perth area (Fairbridge 1950, Teichert 1967, Seddon 1972.)

Eaton Sand

This name is proposed for the yellow to orange quartz sand that overlies the Tamala Limestone.

Derivation of name: After Eaton townsite grid reference 370882 Collie, 1:250 000 sheet.

Type Section: The type section is designated in a deep road cut (grid reference 372895 Collie, 1:250 000 sheet).

Distribution; Geometry and thickness: The Eaton Sand generally is the surface material of the hinterland and forms a ridge-like body over 10 m thick along the eastern shore of Leschenault Inlet due to marine reworking along a former shoreline (Fig. 1C). The sand has been traced a short distance 100 m offshore to below sealevel under the inlet, and bores on the eastern margin of the inlet show that it extends for at least 6 m below AHD. However for the most part its distribution under the inlet is unknown. Cores on the Leschenault Peninsula show that the Eaton Sand is a generally ubiquitous sheet of irregular thickness overlying Tamala Limestone; its variable thickness (1-3 m) is dependent upon local irregularities of the underlying limestone (Figs 3, 4 and 5).

Lithology: The formation is composed largely of a crudely laminated to bedded yellow to orange quartz sand typically with medium and coarse sand-sized grains (Fig. 6); interstitial fine sand and minor clay also occur. The unit contains scattered charcoal, trace fossils (burrows and root casts) and vegetative debris, but mostly it is unfossiliferous. In thicker sections on the hinterland, the unit is composed mainly of fine and medium sand and at depth its colour becomes progressively light yellow, cream and white. Near the water table the sand may be cemented by iron oxides. Small-scale shore erosion along the eastern shore of Leschenault Inlet has locally exhumed these cemented layers.

In some locations, as exposed in excavations along the lowlands adjoining the eastern shore of Leschenault Inlet, the Eaton Sand contains a thin shelly band (*ca* 2 m thick) lightly indurated by calcite cement. Shells collected from this band include *Donax*, *Glycymeris* and *Bulla*. Radiocarbon dating of *Donax* from the band (at locality grid reference 370897 Collie, 1:250,000 sheet) gave an age of $>35{,}000$ BP indicating a Pleistocene age.

Stratigraphic relationships: The formation disconformably overlies the Tamala Limestone. The Eaton Sand commonly exhibits one of three contact relationships with the underlying Tamala Limestone: (1) sharp contact with yellow to orange sand directly overlying limestone, or (2) gradational contact with yellow to orange sand infiltrating the vugular and interstitial network of the limestone to shallow depth (<50 cm), or (3) yellow to orange sand deeply penetrating down solution pipes. The top of the Eaton Sand passes gradationally into the overlying Leschenault Formation.

Age: The Eaton Sand, based on stratigraphic relationships and a radiocarbon date, is Pleistocene.

Discussion: The Eaton Sand under Leschenault Peninsula is blanketing a karst surface cut into Tamala Limestone and is similar to the unit termed Cottesloe Soil and Karrakatta Soil by McArthur and Bettenay (1960) and Bettenay *et al.* (1960). For most of the study area it essentially covers the Tamala Limestone but it has been reworked by coastal processes into a shoestring-shaped body along a former shoreline developed during the Late Pleistocene.

Leschenault Formation

The Leschenault Formation is the name proposed for the estuarine/lagoonal sequence of grey sand, muddy sand and mud that are shelly in layers.

Derivation of name: After Leschenault Inlet.

Type Section: The type section is designated as core site 28 (Fig. 2).

Distribution: The formation forms the modern depositional surface of Leschenault Inlet and also occurs between 2-6 m below AHD under Leschenault Peninsula (Figs. 3, 4 and 5) and Inlet. Locally, the formation occurs as sheet outcrops or as small inliers amongst Tamala Limestone outcrops on the submarine shelf; after severe storms mud clasts frequently are found along the beach indicating erosion of these offshore outcrops. The formation also is found in isolated occurrences as residuals 2-3 m above MSL on the peninsula under the woodland plains (Semeniuk and Meagher 1981 b).

Geometry and thickness: The formation presently is ribbon shaped: 15 km long, at least 2-3 km wide and up to 6 m thick. At its seaward edge it is undergoing marine erosion so that its past geometry is unknown.

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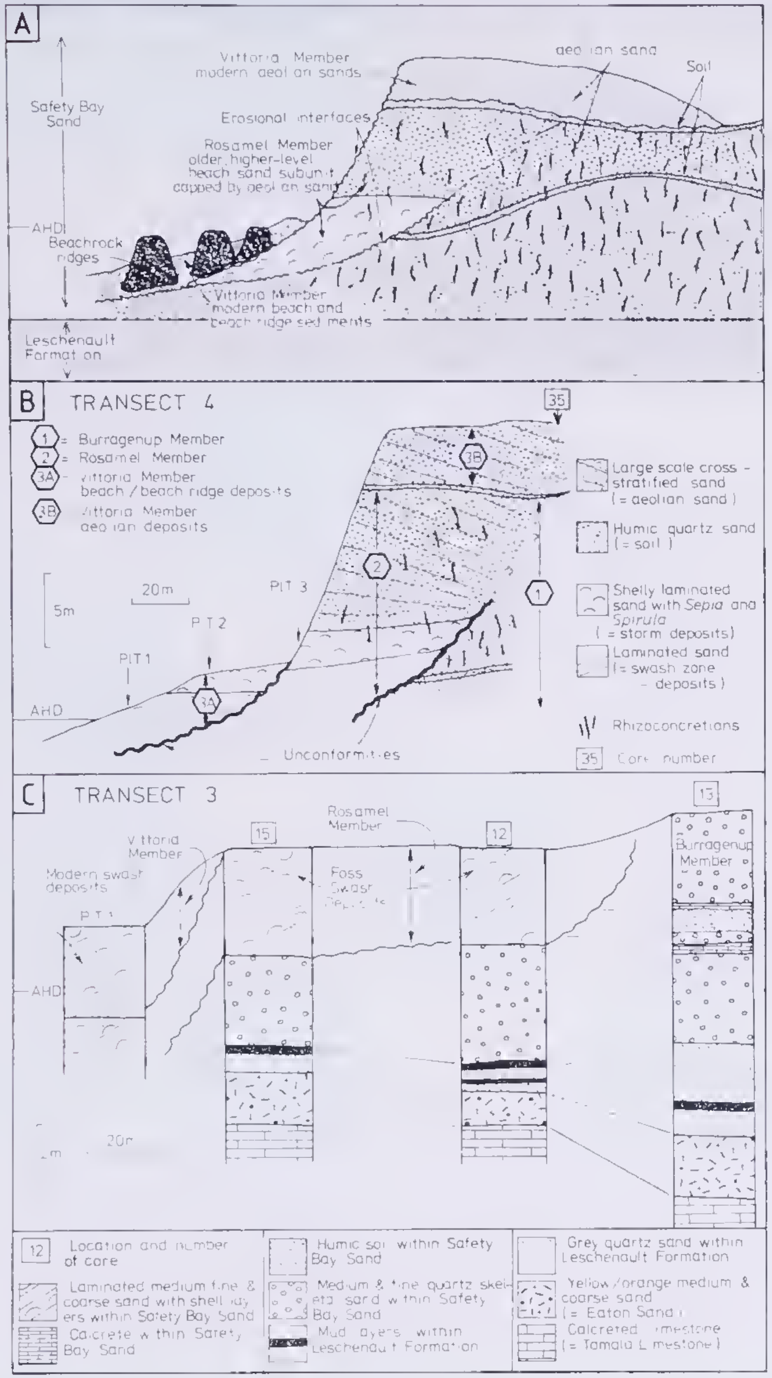

Figure 5.—A. Summary of stratigraphic relationships between members of the Safety Bay Sand.

B. Stratigraphic profile illustrating lithologic sequence within, and stratigraphic relationship between members of the Safety Bay Sand.

C. Stratigraphic profiles illustrating lithologic sequence within, and stratigraphic relationships between Tamala Limestone, Eaton Sand, Leschenault Formation and members of the Safety Bay Sand.

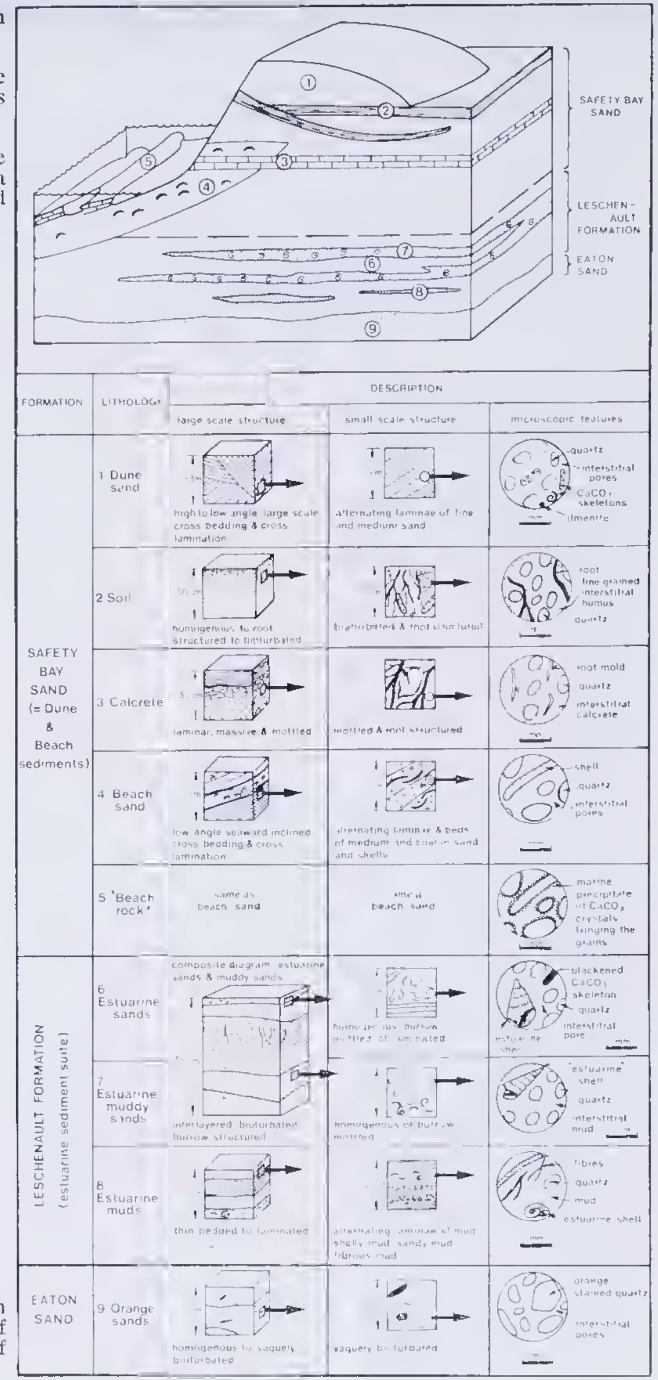

Figure 6.—Summary diagram illustrating characteristics, in terms of structure, fabric, texture and composition, of sediment types in the youngest 3 Quaternary units of the Leschenault area.

Lithology: The Leschenault Formation is composed of grey to dark grey sand (quartz skeletal and quartz), muddy sand and mud, which all may contain shells in layers; sedimentary structures include interlayering laminat.on and mottling (Fig. 6). The mollusc fauna (bivalve and gastropod) indicates estuarine, lagoonal or inlet environments. Several additional criteria serve to characterise sediments of this formation: 1) plant remains, specifically root fibres, 2) bioturbation structures, varying from well preserved burrows to burrow-mottle structures, and 3) iron sulphide disseminated in the sediments.

The abundance of sediments in the formation is as follows: sand > muddy sand > shelly sand > shelly mud and mud.

From east to west under Leschenault Peninsula there are facies changes in the formation. Mud and muddy sand are less common in the west where sandy sediment predominates (Figs 4 and 5). The end-member components of this lithologic suite are sand, mud and shell. Muddy sand is merely a mixture of 2 end-member components. Sand is medium and, less commonly, fine and very fine sized. The sand-sized skeletal component varies from 1% to 30%; sand composition varies therefore from quartzose to quartz skeletal. Shelly sand is similar to the sand but contains granule-sized whole estuarine gastropods, coarser sized estuarine bivalves and fragments of these shells; shells are scattered randomly through the sediment. In addition to gastropods and bivalves there is an abundance of sand-sized skeletons, floral remains and microflora in this formation. Much of the sand-sized skeletons (fragments and foraminifers) are reworked from calcareous dunes on the west margin of the depositional inlet. Most species of flora and fauna in cores or outcrops are extant.

Mud is dark grey to brown and composed of clay-sized and silt-sized particles. Frequently it is laminated, contains root fibre layers and estuarine shell layers. Mud particles are of two types: the most common is clay mineral; the other is silt-sized skeletal material. However, mud that is a homogenous and mottled mixture of these two types also is encountered. Thus, within the mud sediment suite, the mud-sized fraction may be—

- non calcareous (composed of clay minerals)
- slightly calcareous
- calcareous (composed of silt-sized $CaCO_3$)

Where bioturbation is present sediments are either mottled mixtures of the above sediments or thoroughly bioturbated and homogenous. When burrowing has not been intense, layering and lamination are present. *In situ* rootlets and accumulation of fibrous root hairs locally are abundant, especially in the muds. Sediment layers are lenticular and individual layers are not traceable for large distances. Numerous sand-filled burrows (1-3 cm diameter) may extend down several centimetres through a number of layers.

The stratigraphic distribution of sediment types in this formation is best described by the core sequence at site 28:

AHD
−2.3 m

Top: Light grey medium quartz skeletal sand; Horizontal lamination	25cm
Dark grey mud (clay)	25cm
Interlayered and mottled skeletal quartz sand and muddy sand; shelly in layers	30cm
Unrecovered interval	50cm
Interlayered and mottled skeletal quartz sand and muddy sand; shelly in layers	50cm
Light grey medium quartz skeletal sand	90cm
Interlayered and mottled grey, fine and medium sand and muddy sand; fibrous mud laminae	40cm
Grey mud (clay)	20cm
Grey muddy quartz skeletal fine sand	20cm
Grey quartz skeletal fine sand	20cm
Grey mud (clay)	15cm
Grey medium quartz skeletal sand	45cm
Grey mud (clay) and muddy sand filled burrows	20cm
Interlayered fine and medium quartz skeletal sand	20cm
Grey mud (clay) and muddy sand punctured by sand filled burrows	20cm
Grey, shelly quartz skeletal sand	20cm

Bottom: medium and coarse quartzose sand of the Eaton Sand.

Stratigraphic relationships: The base of the formation usually lies on the Eaton Sand and less commonly on the Tamala Limestone; rarely, in southern areas it rests on the Australind Formation (where both Eaton Sand and Tamala Limestone are absent, presumably due to erosion). The contact with Eaton Sand under Leschenault Peninsula is gradational due to biogenic mixing by burrowing organisms; orange sand grades up into grey (pyritic) sand and this in turn grades into grey sand mottled with muddy sand. On the east margins of Leschenault Inlet the formation is a contemporary deposit and interfingers with sand reworked off the ridge of Eaton Sand. The contact of the Leschenault Formation with the Tamala Limestone is sharp with pebbles of limestone incorporated into the base of the Leschenault Formation; locally sediment of the Leschenault Formation infiltrates cracks and fissures in the top 50 cm of Tamala Limestone.

The Leschenault Formation under Leschenault Peninsula has a sharp contact with the overlying Safety Bay Sand; this contact is mostly at 2-3 m below AHD. On the eastern margin of Leschenault Peninsula the formation interfingers with modern dunes of the Safety Bay Sand as they encroach into Leschenault Inlet; this contact is 0.3 m above AHD. At some localities on the woodland plain the contact is 2 m above MSL.

Age: The following molluscs have been identified from the formation (G. W. Kendrick 1979, pers. comm.): *Acteocina* sp. A, *Acteocina* sp. B, *Alaba monile* (A. Adams), *Alaba* sp., *Bittium icarus* (Boyle), *Bittium granarium* (Kiener), *Diala lauta* (A. Adams), *Elachorbis tatei* (Angus), *Hydrococcus graniformis* Theile, *Katelysia scalarina* (Lamarck), *Nassarius pyrrhus* (Menke), *Potamopyrgus* sp., *Sanguinolaria* (*Psammotellina*) *biradiata* (Wood), ? *Tawera* sp. (fragment) and *Thalotia conica* (Gray). This fauna is Quaternary (G. W. Kendrick pers. comm.).

The top of the formation in Leschenault Inlet is currently depositional and is Holocene. However there are sheets and outliers of Leschenault Formation 2-3 m below and 2 m above present depositional sites. These deposits on basis of their relationship to the Safety Bay Sand are inferred to be mid to late Holocene.

Discussion: Cores from Leschenault Inlet in an area of active sand and mud deposition (see Fig. 5 of Semeniuk and Meagher, 1981b) illustrate that the sedimentary sequence under Leschenault Peninsula has modern analogues. Individual facies are indicative of water depth (Table 2). Along the modern inlet margin decimetre-thick sand layers alternate with mud layers; the sand has accumulated in tongues and sheets and has been derived from the adjacent shoreline. The interior deeper water basin is accumulating mud. In areas transitional between sand shoals and the interior mud basin, are muddy sands. As active sand deposition alternates with mud deposition, a sequence typical of the Leschenault Formation accumulates replete with shells and burrow imprints of the resident benthos.

Cores under Leschenault Peninsula also indicate a facies change from east to west within the Leschenault Formation when sealevel stood 2-3 m lower than present. Muddy areas occurred predominantly to the east with sandy areas to the west. The facies change indicates that there was a sand peninsula further offshore that barred the wider ancient Leschenault Inlet from the ocean. The barrier shed sand into the inlet so that the Leschenault Formation adjoining the barrier was sandy (environmentally equivalent to the modern subaqueous platforms and shoals). Thus, the eastern margin of the ancient dune barrier is inferred to have been at least 0.5-1 km further offshore, and the crest of the barrier may have been 1-2 km offshore. Further evidence for this barrier and the corollary, a wider Lesechnault Inlet, is to be found in the Leschenault Formation muddy sediments (indicative of interior mud basin environments) and faunal remnants now occurring up to 0.5 km offshore on the submarine shelf.

Safety Bay Sand

The Safety Bay Sand is a unit of aeolian, beach and shallow marine sand and shelly sand. The formation, first defined near Rockingham by Passmore (1970), was extended by Playford and Low (1972) to include all similar deposits in the Perth Basin.

Distribution: The Safety Bay Sand is distributed over more than 30 km^2 on the peninsula and within 0.5 km of the submarine shelf, and it extends well out of the area of study.

Geometry and thickness: The top of the formation is hummocky to planar corresponding to modern depositional and hiatus surfaces. The base of the formation is subplanar (Fig. 4). Its geometry on Leschenault Peninsula and nearshore submarine shelf is ribbon-shaped with dimensions 10 km long, 400-1 000 m wide and 30-40 m thick.

Lithology: Sedimentary material typical of the Safety Bay Sand are (Fig. 6):

1. quartz skeletal sand
2. humic quartz sand
3. calcreted sand
4. medium and coarse sand and shelly sand
5. beach rock.

Quartz skeletal sand (dune sand) comprises most of the formation. The sand is cross-bedded and cross-laminated on a dune scale and has an overprint of root structures. Individual cross-laminated units are wedge-to shoestring-to lens-shaped, varying 10 cm to several metres in thickness, and are separated by erosional discontinuities and soils. The sediment is light yellow to cream, and composed of medium sand with lesser fine sand. Locally laminae contain platy granule-sized shells. Quartz is dominant (approximately 80% to over 99%). A light coating of iron oxide on quartz and $CaCO_3$ grains imparts a light yellow colouration to the sediment.

Humic quartz sand (soil) occurs as sheets (0.3-2.0 m thick) throughout the Safety Bay Sand. They are dark grey to brown, bioturbated and composed of medium and fine sand-sized quartz. There is interstitial humus and root hairs. Calcreted sand occurs as a widespread sheet within the formation near the top of the water table (1.5 m above AHD). The sheet invariably has mottled, massive, laminar and brecciod structures (Semeniuk and Meagher 1981a). Calcrete in mottled and rhizoconcretionary (= rhizotubular) structure also occurs well above the water table (2.0-30 m above AHD).

Table 2

Key stratigraphic contacts and environmentally significant sequences that are related to specific levels relative to AHD*

Type of sequence	Environmental significance	Deposition site relative to A.H.D.
Dune sand overlying thick soil with *in situ* tree trunks	Indicating dune encroachment on a vegetated plain; subaerial	2–5 m above AHD
Cream-light yellow dune sand overlying grey Leschenault Formation sand	Indicating dune encroachment into inlet; shoreline	Contact is approximately 0·3 m above AHD
Sand of Leschenault Formation overlying thick mud	Indicating shoal encroachment into interior basin; subtidal	Contact 1·5–2 m below AHD
Shoaling sequence† of trough bedded sand and gravelly sand overlain by laminated sand and shelly sand, overlain by gravelly sand with *Spirula* and *Sepia*, overlain by dune sand	Indicating beach shoaling from subtidal through the swash zone up to storm level and subaerial aeolian	Subtidal, tidal, storm tide level, and supra-tidal
Yellow/orange sand overlying limestone	Indicating subaerially exposed limestone with shallow sand cover	

* These sequences aid in the palaeo-environmental interpretations of the stratigraphy. Specific stratigraphic contacts where found in cores or cliff exposures indicate palaeo-environments or indicate position of former sealevels.

† This sequence is described in more detail in Semeniuk and Johnson (1982)

Medium and coarse sand and shelly sand (beach sediments) are light yellow to orange, laminated, cross-laminated and cross-bedded units. They are bedded on a decimetre scale, with layering inclined seaward. The sediments are composed of quartz, skeletal fragments and whole shells. Beach rock is similar to beach sediments described above, but has been indurated by marine carbonate (Semeniuk and Meagher 1981b).

Molluscs and sand-sized skeletons occur mainly in the beach and shallow marine sediments. Sand-sized skeletons reworked from the beach face are present in the dune sands. Fossil stumps of tuarts (*Eucalyptus gomphocephala*) and peppermints (*Agonis flexuosa*) occur *in situ* on buried soils in the stratigraphic profile (see Figs. 8A and 9 in Semeniuk and Meagher 1981b).

Stratigraphic relationships: The Safety Bay Sand conformably rests on, and locally interfingers with, the Leschenault Formation (Figs. 4 and 5). The base of the formation lies mostly at 2-3 m below AHD; the modern base lies at about MHW. The top of the Safety Bay Sand is the modern surface.

Detailed study has shown that there are 5 distinct and mappable lithological and/or diagenetically altered units within the formation. Each of these units are related to a discrete historical phase when sea-level stood 2-3 m below, 3-4 m above, and at the present level. It is proposed here to subdivide the Safety Bay Sand into 5 members: these are: Burragenup Member, Rosamel Member, Vittoria Member, Keombana Beach Rock, Binningup Calcrete.

Burragenup Member (named after Burragenup district, grid reference 371895 Collie 1:250 000 sheet).

The Burragenup Member, up to 40 m thick, is the oldest member in the Safety Bay Sand. It is a unit of aeolian sand and soil sheets and underlies most of the peninsula. Its distinguishing characteristics are:

(1) it is partly indurated along laminae such that up to 30% of the profile may be lithified; abundant rhizoconcretions;

(2) its contact with Leschenault Formation is at *2-3 m below AHD* showing that it was deposited with sealevel at 2-3 m below present; its top is variably eroded but it may extend to 35-40 m above AHD.

The Burragenup Member has a conformable prograding contact with older portions of the Leschenault Formation (Figs. 5 and 6); on the east margin of the peninsula the contemporary Leschenault Formation overlies it (Fig. 7). It has an erosional discordant contact with Rosamel Member and a sharp contact (marked by soil) with Vittoria Member.

Rosamel Member (named after "Rosamel" property, grid reference 371897, Collie 1:250 000 sheet).

The Rosamel Member, up to 15 m thick, is littoral sand/beach-ridge/dune unit and it occurs as a wedge cropping out on the western face of the peninsula. Its characteristics are:

(1) uncemented sand and shelly sand with patchy development of rhizoconcretions; shells include *Donax*, *Donacilla* and *Glycymeris*;

(2) within the member there is a shoaling sequence of sediments (Semeniuk and Johnson 1982); dune sand overlies beach ridge and storm gravelly sand (with *Spirula* and *Sepia*) which overlies swash zone shelly sand laminite and subtidal trough bedded gravelly sand;

(3) the individual facies of this member occur *3-4 m above their modern counterparts*, thus the member was deposited with sea-level 3-4 m higher than present.

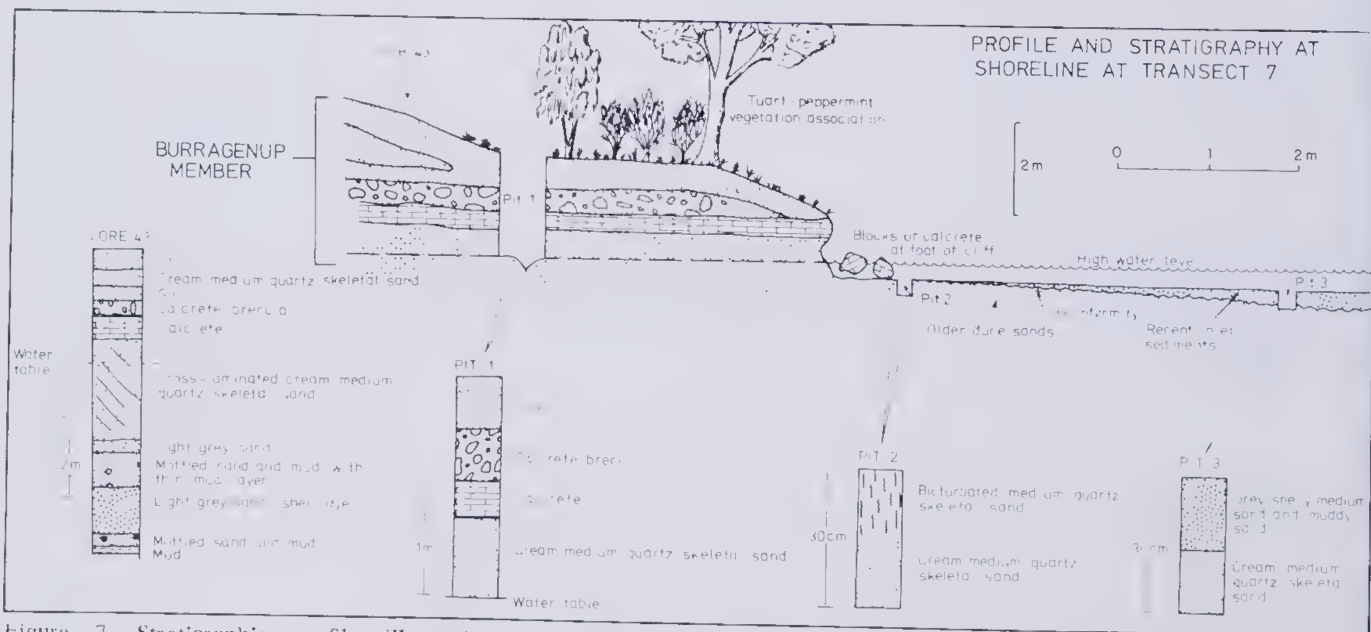

Figure 7.—Stratigraphic profile illustrating relationship of Burragenup Member of the Safety Bay Sand to older deposits of the Leschenault Formation (Core 43) and younger deposits of the Leschenault Formation (pits 2 and 3).

The Rosamel Member has an erosional contact with underlying Burragenup Member (Figs. 4 and 5) and an erosional contact with overlying Vittoria Member (Fig. 5). The outcrop of Rosamel Member widens northward and the unit also pinches out to the east. The unit was deposited along a shoreline oriented NNE. Toward the south the unit occurs only as inliers in interdune depressions of the Burragenup Member, showing that the palaeo-shoreline nearly is totally eroded away in these localities.

Vittoria Member (named after Vittoria Bay, grid reference 366883, Collie 1:250 000 sheet).

This is the modern beachridge and dune sequence of the Peninsula. Its characteristics are:

(1) aeolian and beachridge sands and related soil sheets, totally uncemented and lacking rhizoconcretions;

(2) forming with sealevel standing as at present.

This member overlies Burragenup and Rosamel Members with a sharp contact.

Typically partly indurated, root-casted and calcreted sediment of the older members are truncated by a humic soil over which the Vittoria Member rests (Figs. 4 and 5).

Koombana Beach Rock (named after Koombana Bay, grid reference 365885, Collie 1:250 000 sheet).

This is the modern sequence of beach rock developing along the shoreface of the peninsula and forming the shallow rocky reefs in the nearshore environment (see Fig. 10, in Semeniuk and Meagher 1981b). The sediment of the member is sand and gravelly sand cemented by magnesian calcite. The sand and gravelly sand are in a shoaling sequence showing shallow subtidal sand laminites underlain by trough-bedded gravelly sand and sand. The Koombana Beach Rock unconformably overlies the Tamala Limestone and remnants of Leschenault Formation.

Binningup Calcrete (named after Binningup Beach, grid reference 368902, Collie 1:250 000 sheet).

This is the widespread sheet of calcrete (0.3-0.5 m thick) that occurs just above the modern water table (Semeniuk and Meagher 1981a) and is related to a historical phase associated with the modern sea-level. Since it is parallel to the water table it transects stratigraphic boundaries and unconformities. The Binningup calcrete is exposed by cliff erosion on the ocean side of the peninsula, and locally also occurs cliffed on the inlet side.

Discussion: The disposition of members shows that the barrier dune system of Leschenault Peninsula was developed in 3 stages. All sediments in the formation have modern analogues most of which are forming in specific environments relative to AHD (Table 2). Thus it is possible to infer the relative position of former sea-level and/or water table when each of the members was deposited.

Radiocarbon dating of shells in the Rosamel Member gave the following ages:

3 845 ± 195 yrs BP on shells from site 31 (Fig. 2)

3 610 ± 190 yrs BP on *Donacilla* shells from site 15 (Fig. 2)

4 025 ± 195 yrs BP on *Glycymeris* shells from site 15

4 770 ± 210 yrs BP on *Glycymeris* shells from near site 4 (Fig. 2).

These indicate a late Holocene age. Since this member rests on an erosional interface cut into the underlying unit, the radiocarbon ages indicate deposition of Burragenup Member some time earlier in the Holocene. Unfortunately at this stage no material for dating has been obtained from the Burragenup Member. The Vittoria and Koombana Members are clearly contemporary. Charcoal and wood from three localities in the Vittoria Member gave the following ages:

$<$ 100 yrs BP from soil 3 illustrated in Fig. 9B of Semeniuk and Meagher (1981b)

$<$ 100 yrs BP from near "The Cut", Fig. 1

295 yrs BP from near "The Cut", Fig. 1.

The development of the Binningup Calcrete is related to the modern sea-level and it has formed under the present climatic/oceanographic regime. Presumably the climate was sufficiently different (possibly more like Perth) earlier in the Holocene to preclude calcrete development.

Quaternary history

The Quaternary history of sedimentation for this area begins at the buried surface of the Mesozoic Warnbro Group. Weathering and erosion modified the top of the Warnbro Group to form an undulating surface with local relief in the order of 5 m over several kilometres. The calcareous sands and muds of the Australind Formation were deposited in the mid Pleistocene over the weathered plain; the sediments are thickest where they filled depressions in the plain. Sediments of the Australind Formation have their modern analogy in near-coastal lakes or lagoons suggesting that the Australind Formation developed as calcareous fill in a chain of saline lagoons not unlike the modern Leschenault Inlet. The shelly (fossiliferous) phases represent normal marine or estuarine conditions. Subsequent subaerial weathering/erosion of the Australind Formation formed colluvial soils, with nodules reworked from the calcareous parent sediments, and developed an undulating topography with local relief in the order of 5 m.

The Pleistocene Tamala Limestone, was the next unit to accumulate. It extended from at least several kilometres east of the present Leschenault Inlet to several kilometres offshore. The formation pinches out to the south, an area where it may be expected to be juxtaposed against a ridge of Bunbury Basalt. The history of the formation is a complex one of alternating marine sedimentation, aeolian sedimentation, soil development, alteration in a fluctuating fresh water system, induration by cementing agents, marine and aeolian erosion and colonization by coastal vegetation. These events are imprinted in the sediments as shell and aeolian sand deposits, open and filled cavity systems, calcrete products, sparry calcite cements, wind deflation deposits, calcreted root structures and so on.

During periods of subaerial exposure, the Tamala Limestone was indurated by calcrete and sparry calcite. The induration was localised as a sheet in upper parts of the profile and tended to grade downwards into unconsolidated host sediments. Subaerial exposure and solution of indurated limestone developed cave and vug systems which were filled later by infiltrating marine and vadose-water transported calcareous sediment. At the top of the formation is a major unconformity, marked by extensive calcrete, erosional surfaces, solution features, colluvial gravel and large scale karst.

The Eaton Sand was deposited, probably by aeolian action, as a sheet over the Tamala Limestone (Fig. 8A). The topography at this stage was similar to

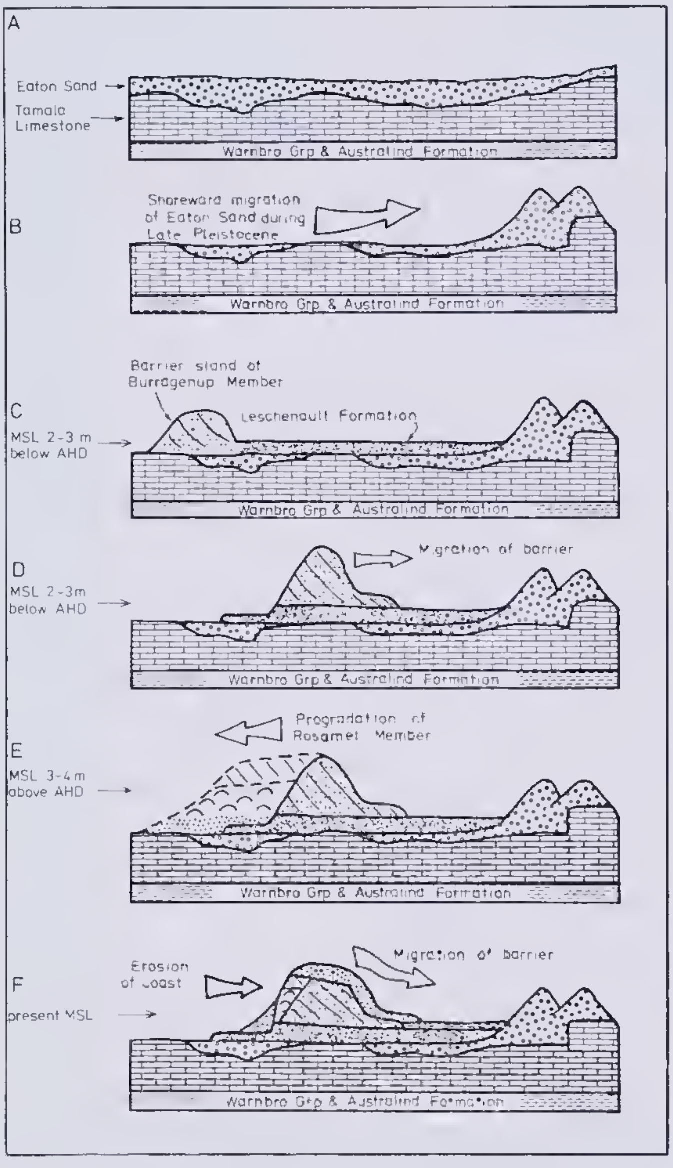

Figure 8.—Summary of Quaternary sedimentation in the Leschenault Inlet area in post-Tamala Limestone time.

"The Pinnacles" (near Cervantes) or the "Little Desert" at Mullaloo; limestone pinnacles and knolls poke up through a sheet of yellow quartz sand, and pavements of limestone are exposed locally. A similar topography of pinnacles is exposed underwater some 300 metres offshore.

The Eaton Sand was reworked as a shoreline deposit forming a coastal ridge system during a marine transgression in the Late Pleistocene (Fig. 8B). Prior to the emplacement of Eaton Sand, a large coastal cliff was cut into Tamala Limestone probably during the initial stages of this trangression. The buildup of Eaton Sand suggests open ocean wave-dominated conditions with sustained aeolian activity onto the shoreface, a palaeogeographic setting which would *preclude* an offshore barrier. It implies there was a marine stillstand after deposition of Tamala Limestone but prior to the development of coastal barrier dune systems that formed the Safety Bay and Leschenault Formations.

The last phases of deposition involved the Safety Bay Sand and Leschenault formations. The deposition and historical development of the Leschenault and Safety Bay formations are linked in that: the Leschenault Formation must accumulate behind a barrier of Safety Bay Sand and, the Safety Bay Sand by eastward migration ultimately progrades over Leschenault Formation. The stratigraphic relationships of the two formations (relative to AHD) and the ages determined by radiocarbon dating of the younger members indicate that the barrier dune system and sediments of the lagoonal/estuarine system were developed in three stages. The first stage, earlier in the Holocene, involved deposition of lagoonal/estuarine sediments behind a barrier dune system when sealevel stood 2-3 m lower than present (Fig. 8C). Initially, as indicated by facies in the Leschenault Formation, the coastal barrier stood some 2-3 km further offshore but with *still-sand conditions* the dunes of the Safety Bay Sand (Burragenup Member) migrated eastward until their eastern edge reached approximately the position the eastern margin of the peninsula occupies today (Fig. 8D).

The next phase of deposition took place with sealevel 3-4 m above present. The marine incursion initially resulted in erosion and trimming back of the dune terrain. The dune terrain however was not totally removed, so that an inlet or lagoon remained intact behind a much reduced (narrow) barrier. In the longterm however there appeared to be a net coastal progradation on the west side of the barrier, with accumulation of shoaling sequence (Rosamel Member) of subtidal sand, beach sand, beach ridge and finally, a capping of aeolian sand (Fig. 8E). This marine/aeolian deposition took place along a coastline of Burragenup Member oriented NNE; probably the coastline was linked to Casuarina Point. The details of sedimentation along the palaeo-shoreline at the onset of the marine incursion are preserved locally. Littoral sand of the Rosamel Member was deposited within corridors (interdune depressions) between east-west oriented dunes: these deposits essentially accumulated in small embayments. Soil sheets of the Burragenup were truncated by erosion during the marine incursion but in some areas soils were merely reworked and locally incorporated into the overlying strandline marine deposits.

During accumulation of Rosamel Member there was concurrent deposition of Leschenault Formation sediments. These are preserved onshore as stranded shelly sand (with estuarine shells) and minor mud deposits located now up to 2 m above AHD. Most of these deposits however are reworked, or overprinted by pedogenetic processes, or buried by later dunes.

The final depositional stage for this area is the current marine incursion (Fig. 8F). This involves accumulation of lagoonal/estuarine sediment of the Leschenault Formation, eastward dune progradation and development of beachrock and calcrete. Erosion and net northward sediment mobilization however are the major processes along the seaward edge of the barrier dune system today. As the barrier retreats eastward, sediments of the Leschenault Formation are being exposed and cliffed, and exhumed ridges of beach rock are left as outliers on the submarine shelf. Under the modern climatic and hydrologic regime a calcrete sheet is forming just above the water table on the peninsula. This calcrete is essentially a water table phenomenon related to the present sealevel and it transects the various member units of the Safety Bay Sand and the erosional interfaces between them.

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